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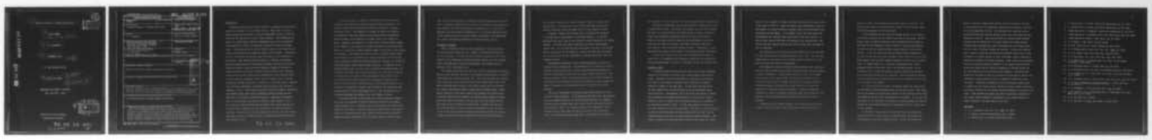

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Contacting metal surfaces subjected to pressure and relative motion suffer from a phenomenon known as fretting corrosion. When one of the two surfaces is also subjected to cyclic stress this phenomenon can lead to premature fatigue crack initiation and is known as fretting fatigue. Important variables in this process are the magnitude of relative displacement, contact pressure, frequency, relative hardness of contacting surfaces, intrinsic fatigue resistance and possibly environment and temperature.

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Introduction

Engineering materials are often subjected to operating conditions which require two surfaces to be in intimate contact. When there is relative motion between the two surfaces, a peculiar phenomenon, known as "fretting corrosion" has been shown to occur in many instances. This phenomenon can result in a large range of material degradation from a mere discoloration of the surfaces in contact to premature initiation of high cycle fatigue cracks. The faying action of the two surfaces results in the production of oxides which accelerate the mechanical damage of the surfaces. Additionally the local wearing away of material exposes new metal to the environment to be oxidized. Thus fretting corrosion exhibits a symbiotic relationship where the wearing action of the surfaces increases corrosion rate, and the corrosion product in turn accelerates mechanical damage of the material. Fretting corrosion (of steels) has been shown to increase with increasing normal pressure on the surface under consideration, with increasing number of cycles and with increasing relative motion (termed "slip" in fretting terminology) between faying parts. Conversely, it has been shown to decrease with increasing temperature, increasing relative humidity and increasing frequency (in air). These results have been utilized to propose a mechanical/environmental model where strictly mechanical effects dislodge material which acts as an abrasive between faying parts. Aggressive environments serve to oxidize some of the metallic particles thus producing a still more effective abrasive between mating surfaces since oxide particles are, in general more voluminous and less resistant to flow than are metallic particles. Rapid oxidation of clean surfaces takes place since the rubbing and abrasive action of trapped particles continuously produces fresh oxide free surfaces [1-13].

It has been shown by a number of investigators that this fretting corrosion, when applied to surfaces undergoing fatigue deformation, can result in rapid crack initiation and accordingly decreases in fatigue resistance [13-15]. This decrease in fatigue resistance was thought to be a function of both the hardness of the material under consideration and the hardness of the material in intimate contact (see Progress to Date). Typically, for instance 0.1 C steel with a Vickers hardness number of 127 exhibits a 40% reduction in fatigue resistance at the fatigue limit while 0.7 C steel with a Vickers hardness number of 270 shows a 110% decrease in resistance. Cold drawing the steel to obtain a Vickers hardness number of 365 results in a 218% reduction in fatigue resistance with the fatigue limit occurring at 20,000 psi alternating stress in contrast to a 70,000 psi alternating stress under normal fatigue conditions. A comparison of the fretting fatigue limit of 0.16 C steel in contact with aluminum (VHN = 31) or with Cu-10Al (VHN = 289) shows a drop from 1.25 x 10^6 cycles to failure to 30,000 cycles to failure at the predetermined fatigue limit in air. As in the case of fretting corrosion in the absence of applied cyclic stress to the test piece, fretting fatigue crack initiation appears to be related to the magnitude of normal load sustained by the interfacial area, the amplitude of relative displacement (up to 7 μm), the presence of an oxidizing atmosphere and frequency [16] (see Progress to Date).

It has been pointed out that there are at least seven major theories which have been advanced to describe fretting corrosion and accordingly fretting fatigue [17]. In general, these can be divided into models which depend on cold welding or adhesion between the surfaces which subsequently result in the breaking off of small particles which are then oxidized to produce the debris observed [1,2-5], and models where the metal is worn away and the fretting surface is oxidized, the oxide subsequently being worn away to produce an abrasive [6,9]. The role of oxidation in the process has been disputed, with some investigators concluding that it is only mildly important [15] while others concluding that it is of prime importance [8,9]. A more complete discussion of these factors is provided in the proceedings of a recent International Conference on Corrosion Fatigue [16,17].

Statement of Problem

While a significant amount of data pertaining to fretting corrosion has been generated, there are still a number of controversies which have yet to be resolved. In particular some of these controversies involve the specific role of fretting in nucleating fatigue cracks, the role of normal stress, the amplitude of relative displacement, the frequency and the character of the environment [16].

For example, Waterhouse has shown that, for his experimental procedures, fatigue cracks generally initiate at an interface between regions of relative displacement and stationary regions [18]. This model specifies that fatigue crack initiation results from local high strain fatigue which arises from high alternating shear stresses in the contact region and is accentuated by a stress concentration between slipped and non-slipped regions. Mathematical analyses of this model indicate that materials with high fatigue resistance should be more resistant to fretting fatigue damage but experiments have shown the converse to be the case, with cold worked materials being more severely affected by fretting [18]. Hoeppner has shown that the crack may initiate at the slip/non-slip boundary but feels that this is due to the region showing the maximum displacement between the fretting surfaces and that the stress concentration arises from the discontinuity in the loading rather than a strictly geometric affect of surface stress concentration. In some cases it has also been shown that cracking may initiate completely inside the damage zone [17] (see Progress to Date).

In general, fatigue life has been shown to decrease with increases in the amplitude of displacement of contacting surfaces. It has been postulated that this is due to the increase in debris produced by the faying surfaces. For steels this effect stabilizes at relative displacements greater than 7 μm; this stabilization would appear to be due to the wearing away of crack nuciei in the surface at a faster rate than they are formed. This conclusion has not been experimentally demonstrated however [16] (see Progress to Date).

Decreasing the frequency of cyclic stressing produces a decrease in fretting fatigue strength [16]. This observation is in contrast to results obtained on fretting corrosion of steels where decreasing frequencies of relative displacement has been shown to increase weight losses [8,9]. The fretting corrosion results were explained on the basis of high frequencies inhibiting the time available per cycle for oxidation to occur, however the effect of frequency on fretting fatigue crack initiation has not been examined.

The role of environment on fretting fatigue crack initiation is also an area of some controversy. It has generally been shown that inert environments are somehwat beneficial to fretting fatigue behavior, but Hoeppner concludes that environment plays only a minor role in fretting fatigue [17] (see Progress to Date). In fretting corrosion in the absence of cyclic stresses however, environment has been shown to be a very significant factor in determining specimen weight loss. This effect may be related to test frequency but this hypothesis has not been experimentally verified [19].

The effect of temperature has not been adequately examined and is also a controversial subject. Waterhouse, for example, has shown that fretting may result in recrystallization of surface grains in steels, and has concluded that interfacial temperatures may be as high as 500°C [20,21]. Wright, on the other hand, has shown that fretting damage of steels can occur when the steel is in contact with PMMA, a material which has a melting point ≈ 80°C [12,20](see Progress to Date). Additionally, it has been shown that weight losses increase with decreasing ambient temperature.

In view of the controversies and lack of fundamental knowledge in these areas it is suggested that a program to understand and characterize fretting fatigue damage in steels is a pertinent subject for further study.

Progress to Date

A fretting fatigue apparatus has been built which allows independent variation of the extent of relative slip, normal pressure and stress or strain. Experiments have been performed on a normalized (spherodized) 4130 steel in the annealed conditions, and on quenched and tempered martensitic samples of the same steel. In both cases fretting debris has been identified by x-ray diffraction to be the anticipated γFe_2O_3 and Fe particles. Interestingly, the Fe particles often appear as flakes, with extensive microcracking being observed. On the basis of results obtained to date, it appears that the fretting process is an extension of the delamination theory of wear. In other cases spheres of metal have also been identified in the fretting debris. The effect of normal pressure at constant slip displacement has been studied with the result that increasing normal stress tends to slightly improve fatigue resistance. The effect of relative slip has also been studied with the result that there appears to be a minimum in fatigue resistance associated with relative slip in the range of 20-40 μm. Larger and smaller slip displacements result in improvements in fatigue resistance although larger slip displacements show increasing fretting damage. It is assumed at this time that larger slip displacements may eliminate small microcracks in the alloy surface. It has also been observed that some cold welding of the fretting pad to the alloy occurs when applied loads are low, with a "break away" occurring as load is increased.

The temperature of the fretting pad-alloy interface has been measured and the average increase in temperature shown to be $< 20°K$. The interface temperature was also shown to vary in phase with the applied cyclic load and to decrease with time of the experiment.

Metallographic studies of fretted surfaces indicates that significant amounts of metal transfer occurs under the fretting pads with large amounts of plastic deformation. Fatigue cracks initiate at $\sim 30°$ to the surface and propagate at this angle through the plastically deformed material, altering to normal stage II fatigue cracking in the annealed structure. Preliminary analysis indicates that fatigue cracks may initiate when plasticity is exhausted in the alloy surface. Cracking in martensitic structures is similar to annealed structures except that considerably less plasticity occurs although extensive bending of martensitic plates is observed.

Examination of the fretted surfaces, cross sections through fretted surfaces, and the wear debris has provided the information necessary to construct a model of the mechanism of material removal in fretting. The fretting model explains the characteristic manner in which fatigue cracks initiate and propagate in fretting fatigue.

It was determined that the annealed specimen surface is cold worked very heavily and pieces of the surface crack away in thin layers, and that several layers of metallic material could be removed from the surface in some areas by the stripping of plastic replicas, indicating the presence of cracks or paths of extreme weakness roughly parallel to the fretted surface. It was also found that fretting fatigue cracks propagated at a low angle to the fretting surface through a surface layer 10 to 20 μm thick. Metallographic cross sections revealed extensive cold work in this surface layer. At greater depth, i.e., below this cold-worked layer, cracks propagated normal to the stress axis of the fatigue specimen. At the initiation site of a fretting fatigue a tongue of material was observed as has often been reported in the literature. This characteristic feature can now be explained as resulting from the initial propagation of the crack at a low angle to the surface.

It is now clear that the process of material removal in fretting and the initiation of fretting fatigue cracks are closely related. Both depend upon the development of cracks nearly parallel to the fretting surface which are apparently related to the cold working of the surface. It is clear that improvement in the resistance of a material to fretting damage and fretting fatigue must come through reducing the susceptibility of the surface layer to such cracking.

In addition to these results, we have shown that, for martensitic structures there is a $\sim$20% increase in hardness below the fretted area which supports a plasticity exhaustion model. We have also shown that models of fretting fatigue which require cracks to initiate at the slip-no slip interface are not necessarily tenable and are probably a function of the test apparatus utilized. This observation is important since it has been observed that fretting fatigue cracks often occur away from that interface in service. Other results which are currently being obtained indicate that the coefficient of friction between the faying surfaces decreases with increasing test time, indicating that the fretting debris acts as a kind of lubricant between the surfaces. We have also observed that, contrary to previous conclusions environmental effects can be quite pronounced in fretting fatigue; an inert environment (Argon) resulting in significant increases in fatigue resistance. These results are preliminary and will be pursued during the remainder of the present contract period. We have also shown that the relative hardnesses of fretting surface may not be as important as had previously been suggested. Spherodized and martensitic structures as well as constantan fretting pads in contact with spherodized fatigue specimens result in essentially identical fatigue resistance. Preliminary transmission electron microscopic observations of regions near the fretted surface indicate a heavily tangled dislocation structure in contrast to the cellular structure observed in the bulk of the steel. These observations support the model of plasticity exhaustion in the fretted surface leading to delamination of the surface layers in a manner analogous to the wear theory of Suh [22].

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